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**DESCRIPTION AND PERFORMANCE OF THE ELECTRICAL  
SUBSYSTEM FOR A 2 TO 15 kWe BRAYTON POWER SYSTEM**

by Pierre A. Thollot, Richard C. Bainbridge,  
and James Nestor  
Lewis Research Center  
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at  
Fifth Intersociety Energy Conversion Engineering  
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Abstract

The electrical subsystem of the 2 to 15 kWe Brayton power system includes the engine control system, the electrical control package, the dc power supply package, the inverters, and required instrumentation. This subsystem has undergone extensive experimental evaluation both on an individual component basis and as part of the complete flight configured power system. Tests were performed under a variety of conditions including high and low ambient temperatures, vacuum and atmospheric pressures, steady state and transient operating modes and at design as well as off-design conditions. The electrical subsystem is described, and performance characteristics of individual components and of the subsystem when mated to the complete Brayton power system are discussed.

Introduction

The NASA Lewis Research Center Brayton-cycle technology program began in 1963. The program has progressed through the design and fabrication stage to the component and system testing stage. Earlier IECEC presentations discussed the various phases of the program. In 1968 a description of the system under development was presented by Klann (Ref. 1). In 1969 a report by Brown (Ref. 2) updated the program status. A report by Klann (Ref. 3) at this year's IECEC Conference compares initial system test results with those predicted by the method of Ref. 4.

The electrical subsystem of this power system regulates and distributes the generated electrical power; plus it provides all control and logic functions required to operate the system. Development of this subsystem was a combined Lewis Research Center-contractor effort wherein overall responsibility for subsystem configuration and design resided at Lewis; and various contractors were responsible for detailed design, fabrication and limited testing of individual components. (See table I for complete list of electrical subsystem component manufacturers.) Presented herein is an overview of the electrical subsystem including a description of each component, their functional interconnection, and test results both on a component basis and when interconnected as a subsystem.

Description of the Brayton System

The Brayton Power System (referred to as engine) discussed herein is a self-contained 2 to 15 kWe electrical power system suitable for space applications. Figure 1 is a schematic representation showing the major subsystems which comprise the power system. The heat source subsystem, which adds heat to an inert working gas may consist of any energy source that can provide heat at the proper temperature. For space applications two energy sources of interest are radioisotopes and nuclear reactors.

Hot gas leaving the heat source heat exchanger flows through a single-stage, radial-inflow turbine. Expansion of the gas through the turbine spins the shaft and produces useful work. About two-thirds of this work is absorbed by driving a single-stage radial-outflow compressor. The remaining one-third of the shaft work is available for conversion to electrical energy by a four-pole solid-rotor alternator mounted on a common shaft with the turbine and compressor. The single shaft of this Brayton Rotating Unit (BRU) is supported by journal and thrust bearings that are lubricated by the working gas itself. After expansion in the turbine, the gas flows through a recuperator where a majority of the unused heat energy is transferred back to the cooler gas leaving the compressor. The gas leaving the recuperator is further cooled by the gas-to-liquid heat exchanger where waste heat is transferred to the heat rejection loop. The main thermodynamic gas loop utilizes an inert gas (a mixture of helium and xenon with a molecular weight of 83.8), as the cycle working fluid to convert thermal power to electrical power. The heat rejection subsystem which utilizes a liquid coolant (Dow-Corning 200), removes waste heat and rejects it to space through a radiator. Circulation of the

liquid coolant through the gas-to-liquid heat exchanger, the alternator housing and a series of four cold plates on which the electrical subsystem components are mounted, is accomplished by a 400 hertz pump-motor assembly. Finally the electrical subsystem regulates and controls power system operation, and will be discussed in detail in the remainder of this report.

In Fig. 2, an electrically heated Brayton system is shown in the vacuum chamber of the NASA Space Power Facility. In this configuration, an electric heat source and a facility cooled heat rejection system are used to test the basic power conversion system which includes the main gas loop and the electrical subsystem. The Brayton system shown in Fig. 2 is undergoing extensive testing at the NASA Space Power Facility and has accumulated a total of 2000 hours of operation as of 5/13/70.

Description of the Electrical Subsystem

The electrical subsystem of the Brayton Power System is a flight-configured, functional part of the power system. It is engine-mounted, self-powered and totally integrated with the remaining subsystems which comprise the basic power system. In summary form, the electrical subsystem performs the following functions:

- (1) It controls and regulates alternator output voltage.
- (2) It maintains line frequency (1200 Hz) within design tolerances by controlling alternator shaft rpm using an electrical parasitic loading technique.
- (3) It distributes and provides switching of all electrical power used for housekeeping and supplied to the user bus.
- (4) It supplies its own internal source of dc power during periods of engine startup, normal steady state operation, and during shutdown.
- (5) It supplies a source of 400 Hz, 45 volt RMS three phase power for heat rejection loop pump excitation.
- (6) It provides signal conditioning for all engine instrumentation.
- (7) It provides for emergency protection of the engine in the event of an overspeed.
- (8) It contains excitation and logic circuits required to operate all engine control devices.
- (9) It provides for fully automatic engine operation with manual overrides for all control functions.
- (10) It contains visual and telemetry-compatible data monitoring capabilities.

Figure 3 is a pictorial representation showing each of the items of hardware which comprise the electrical subsystem. The functions listed in items 1, 2, and 3 above are performed by the electrical control package (ECP). The parasitic load resistor (PLR) in conjunction with the ECP accommodates item 2. The DC Power Supply and batteries provide the function listed in item 4. For reliability, two identical liquid coolant loops are provided, each requiring an inverter to excite the heat rejection pumps mentioned in item 5. The signal conditioner contains all required circuitry to accommodate those functions described in items 6 and 7. Finally the control and monitoring panel provides for the items listed in 8, 9, and 10 above. Some of these components and the interconnecting harness can be seen mounted on the engine in Fig. 2.

Figure 4 is a block diagram of the electrical subsystem showing the interconnection of 120/208 volt 1200 Hz three-phase power,

28/56 volt dc power, and low level instrumentation and control signals. The interconnection of approximately 3000 terminal points is represented in Fig. 4. Details of each of these components will be presented in later sections. However, to assist the reader, a brief discussion describing the interfunctional relation of each unit is presented here.

The signal conditioner interfaces with nearly all other subsystem components. All command signals originating from the control console as well as all instrumentation and monitoring signals including those controlling the Gas Management Subsystem (GMS) are channeled through the signal conditioner. Temperature, pressure, flow, voltage, current and frequency are examples of instrumented variables which are converted to standard 0-5 volt data in the signal conditioner. All control signals for valves, relays or electronic switches pass through the signal conditioner. The control and monitoring functions of the console are so closely related to the signal conditioner, that these two units were designed and fabricated under one contract and are designated the Brayton Control System (BCS).

Engine dc power is provided by an electronic DC Power Supply Package (PSP) during normal operation, and by two 28 volt batteries during engine startup and shutdown. Excitation of most of the control and logic functions, plus power for all electrical devices is derived from this dc source. Plus and minus 28 volts is converted into the 400 hertz power used to drive the pump-motor assemblies of the liquid heat rejection loop by static inverters.

Finally, control, distribution, and regulation of the 1200 hertz, three-phase power of the alternator is accomplished by the electrical control package (ECP), which contains the alternator voltage regulator, distribution contactors, current transformers and speed control circuits. The parasitic load resistor (PLR) dissipates excess power as commanded by the speed control to maintain alternator speed within specified limits.

Each of the electrical components which comprise the electrical subsystem have undergone extensive testing both on an individual component basis and as part of a complete subsystem. Table II presents a summary of test hours accumulated and singles out the maximum hours (in all cases above 2000 hr), on any one unit.

#### Component Characteristics

In this section, each of the components of the electrical subsystem will be described. Inasmuch, as alternator speed control and voltage regulation, and the design and performance of the control system are both subjects of separate papers (Refs. 5 and 6); these items will not be covered in as much as the remainder of the subsystem.

#### Alternator

The alternator is a four-pole, solid rotor, modified Lundell type, three phase machine whose output is 208 volts line-to-line. A turbine and compressor are attached at each end of the alternator rotor to form a single shaft Brayton Rotating Unit (BRU). Gas-lubricated thrust and journal bearings support the BRU shaft which rotates at 36,000 rpm. Alternator cooling is accomplished by dual liquid passages containing the heat rejection system coolant, looped around the alternator housing.

Two field windings are provided; a series field whose excitation is proportional to alternator line current, and a shunt field excited by the voltage regulator as required to maintain alternator line voltage within specified limits. A more detailed discussion of the alternator can be obtained by consulting Ref. 5.

#### Brayton Control System (BCS)

The BCS provides all control and monitoring functions necessary to operate the engine. It consists of two items, an engine mounted signal conditioner and a control and monitoring console. The signal conditioner is an electronic unit which interfaces between all of the engine instrumentation and electrical control devices, and the control and monitoring console. The composite photographs of the electrical subsystem, Fig. 3, shows both parts of the BCS. The signal conditioner accepts all engine instrument and logic signals and converts them to a common 0 to 5 volt dc value. It also acts as the interface

for the returning command and control functions originating from the control console. The link between the two elements of the BCS consists of 11 multiconductor cables. This hard wire link contains 183 sensing signals, 43 return signals, 32±28 volt dc power leads, 43 shields, and 66 spare conductors.

Of all the electrical components, the signal conditioner and control and monitoring console contain more circuitry which interfaces with the remainder of the engine, than any other item of engine hardware. For reliability, critical engine parameters (those on which control action is dependent), are triple redundant. All circuits associated with conditioning these parameters are triple redundant. To assure continued safe engine operation following any single part failure, agreement of two out of three logic circuits is required to initiate a command that will affect engine operation. To thoroughly discuss the design of the BCS is beyond the scope of this paper and has been delegated to a separate paper. Reference 6 specifically deals with the requirements, design and performance of the control system.

#### Electrical Control Package (ECP)

The ECP contains the alternator speed control circuit and the alternator voltage regulator (VR). In addition to these prime functions, the package contains a number of contactors including the vehicle load breaker, and current transformers for measuring alternator and vehicle lead currents. All of these components and/or functions are schematically represented in Fig. 5.

The VR supplies current to the series and shunt fields of the alternator as required for the generation of the correct line voltage. It consists of two current supplies, one for each field. The series field current supply consists of a current transformer on each phase of the alternator output and a bridge rectifier circuit. The current transformers are sized to provide a total series field current that is approximately 0.09 times the average alternator line current.

The shunt field section of the voltage regulator senses the peak line voltage, and compares it with a reference set point to determine the amount of additional field excitation required to provide the required 120 volt RMS line to neutral voltage. The output of the shunt field regulator is a pulse-width modulated voltage which, when applied to the alternator field, results in the required average shunt field current.

The BRU is designed to operate at a constant speed of 36,000 rpm which results in an alternator frequency of 1200 hertz. Since user load requirements are not necessarily constant, and to accommodate small variations in thermal input power, the engine requires a speed control. The form of control utilized by the Brayton engine is electric parasitic loading whereby the speed control diverts excess alternator power to a parasitic load resistor. Specifically, the control is composed of three separate 6 kWe parasitic load control channels that operate over a predetermined band of frequencies. Speed is controlled to within 2 percent of design using two of the channels; the third channel was intentionally included and serves as a backup should one of the other two fail to operate.

Each of the three channels of the speed control are identical, therefore the following discussion will describe only one. A single channel of the speed controller comprises a frequency detector, a preamplifier, an amplifier, and a phase controlled SCR output stage. The output of the frequency detector is a dc error signal proportional to the frequency error. Amplification of this signal is provided by a two-stage push-pull magnetic amplifier. Firing of the SCR output stage is controlled by a saturable reactor. Using this method, firing angle is directly proportional to the output of the final stage of amplification which in turn is proportional to the frequency error. The output of each channel uses phase controlled SCRs as power switches for loading the fixed parasitic load resistor. Additional information related to the ECP is provided in Ref. 5.

#### DC Power Supply

The DC Power Supply is a solid state, flight-configured unit, whose main function is to supply the dc internal power requirements of the Brayton power system. The prime source of dc power is from conversion of alternator ac to dc power by means of transformers and diode rectifiers. There are times when alternator ac power is not

available, e.g., prior to and during a startup condition and during shutdown. During these periods, dc power is still required and is supplied by a pair of AgCd batteries, one for +28 volts and one for -28 volts.

The DC Power Supply also has as secondary functions the requirement to recharge the batteries, provide all the control functions necessary for its operation, and to provide a monitoring capability for the dc power system parameters. The power supply is represented in block diagram form in Fig. 6. Input to the DC Power Supply is from the 3-phase, 1200 Hz, 208/120 volt ac alternator to the primary winding of two 3-phase stepdown transformers. One of these transformers has a wye connected primary and the other primary is delta connected. The secondary windings of both of these transformers have identical 6-phase star connections to supply the battery charger circuits with  $\pm 42$  volts and tapped to supply the engine dc bus with  $\pm 28$  volts; thus the 3-phase input voltage is transformed into a 12-phase voltage and then rectified. The result is an output with low ripple voltage which is acceptable for engine operation without filtering.

The remainder of the DC Power Supply is in reality composed of two halves, each with several duties. One half of the supply is for the positive 28 volt bus and 42 volt positive battery charger, while the other half is for the negative complement of these voltages. The two sections are basically identical and therefore only the positive section will be described in detail. This discussion will follow the block diagram of Fig. 6. The rectifier section of the supply is actually three separate circuits made up of fused diodes. One circuit supplies the rectified 28 volts for the dc buses. Another circuit rectifies 42 volts for the charger circuit. A third circuit rectifies voltage to provide a 28 volt reference signal used by the logic circuits for automatic control of the dc bus relay.

The battery charger circuits utilize the 42 volt dc from the rectifier circuits through a series current regulator to maintain a constant 4 ampere battery charging current. A charger for one battery is made up of two paralleled 4 ampere constant current sources. Each one is individually controlled on and off by the logic circuitry to provide either a 4 amp or a total 8 amp charge rate depending on the state of charge of the battery. Charger on-off command conditions will be discussed as part of the logic circuit description.

The position of the power relay determines the source of 28 volts supplied to the bus. During normal operation the 28 volt bus is supplied from the internal transformer-rectifier circuits which are directly connected to the bus as shown. Should the bus voltage reference signal drop below a given preset level, or during startup and shutdown, the relay logic places the AgCd batteries on the bus as an additional source of power. The relay is also manually controllable to remove the batteries from the bus during extended periods of shutdown, to prevent a needless drain of battery charge.

Figure 7 is a block diagram representation of the logic circuits of the Brayton DC Power Supply. The control logic associated with the battery charger senses terminal voltage and governs the chargers on and off depending on the battery terminal voltage, which is in part a function of state of charge. The setpoints are indicated on the block diagram. There is also a manual control switch to command the chargers full on or full off as required. When the output of the ampere-hour-metering circuit indicates a battery going from 100 percent charge to 90 percent charge, an additional input is provided to the charger logic circuits to turn the charger full on.

Automatic control of the dc power relay is provided by logic circuitry which senses the 28 volt reference signal and compares it to a 24 volt set point. If the reference voltage drops below 24 volts, the relay is automatically switched to the batteries. As shown in the logic block diagram of Fig. 7, the reference voltage must reach a magnitude of 25 volts and remain there for 5 seconds before the relay is opened again. The circuit was designed with an opening delay to hold the batteries on the bus long enough to clear a short circuit that might be loading down the dc bus. As was the case for the battery chargers there is a manual control input to provide override operation of the bus relay.

The two batteries installed on the engine are to provide  $\pm 28$  volt dc power during startup and shutdown, and for backup in the event of

power supply failure. The batteries each have a nominal capacity of 85 amp-hr at 40 amperes, and can deliver up to 100 amperes for a period not exceeding 1 minute. Each battery consists of 25 hermetically sealed silver cadmium cells enclosed in a stainless steel case containing a builtin current shunt.

#### Inverter

The inverter is a solid state, flight packaged unit designed to operate from a 56 volt dc source as provided by the engine DC Power Supply. The output is a 400 Hz, 3 phase, quasi-square wave voltage with a zero dwell time of  $60^\circ$  and peaks of  $120^\circ$  duration when measured phase to phase. Phase displacement is  $120^\circ$  between phases. The inverter is capable of starting and continuously running the 3-phase pump motor at up to 170 percent of the rated 12 ampere pump motor requirement (19.0 amp). Commands to turn the inverter on or off are provided by the BCS by means of a 3 millisecond pulse of 2.4 to 5.0 volts amplitude.

The block diagram of Fig. 8 illustrates the operation of the inverter package. The 56 volt dc power is connected directly to the input terminals. The current passes through a low-pass L-C filter to provide low R, F, impedance to the system neutral, then passes through an audio filter, having a cut-off of approximately 150 Hz, which reduces inverter-induced noise back to the dc bus. This filter also reduces any ripple or modulation that may be present on the dc bus. The low level series regulator supplies voltage to the oscillators and the inverter over-current protection circuit. The regulator also includes the circuits to turn the inverter on or off by remote command.

The ripple regulator contains the voltage sensing and comparator, as well as the trigger and amplifier circuits required to regulate the dc voltage to the higher level required by driver stages, normally 40 to 45 volts.

The oscillator section consists of the phase A, B, and C oscillators which generate the basic 400 Hz frequency for the inverter. The phase A oscillator contains a precision L-C series resonant circuit in which oscillation is started by turn-on, and sustained by regenerative feedback from the output transformer. This oscillator also contains a frequency sensing winding on the coupling transformer, a second winding with a full wave rectifier to provide a bias voltage for the overcurrent protection circuit, and a third winding, which in series with a saturable reactor provides synchronization voltage for phase C and B oscillators.

The driver stage contains three identical amplifiers, each of which amplifies the output from its respective input coupling transformer to drive the power amplifier for each phase. The output section consists of three identical power amplifiers whose output is a square wave, each displaced by  $240^\circ$  from the others. The phase A and B output current pass through the primary of a sensing transformer for the over-current protection circuit before connection to the inverter output terminal, while phase C is directly connected to its output terminal. Phase voltages AB, BC, and CA of the inverter output are the difference of the two square waves comprising each phase voltage, resulting in the quasi-square wave output with  $60^\circ$  of zero dwell. Figure 8 includes typical wave shapes generated at several points within the inverter.

#### Discussion of Test Results

As in the components characteristics section, information reported elsewhere will not be covered in detail. The intent here is to present an overview of the entire electrical subsystem performance with special emphasis on components not covered in Refs. 5 and 6.

#### Alternator

Test results of the alternator research package are discussed in detail in Refs. 5 and 7. Alternator efficiency, as a function of power level, tends to be one to two percentage points lower than originally predicted. It is believed this difference is the result of higher than expected internal losses. Additional data (Ref. 7) shows that for unity power factor loads, the peak efficiency is 93.6 percent at 9.5 kilowatts. Testing of the alternator was performed to determine its electromagnetic performance limits. These tests, reported in Ref. 8,

indicate the maximum alternator electromagnetic capacity to be in excess of 26 kilowatts at a power factor of unity.

#### Brayton Control System

The two units (signal conditioner and control/monitoring console), and the interconnecting cabling which comprise the BCS were designed and fabricated under one contract. This enabled acceptance testing of the two units operating together. Functional testing at ambient temperature and pressure, nominal power, and at maximum and minimum electrical stress levels, was accomplished using a load simulator which supplied all instrument and control device interfaces, which normally are provided by the Brayton engine. Additional testing with the signal conditioner mounted on a standard engine coldplate and installed in a vacuum chamber was performed over a range of coldplate coolant temperatures. In this manner the adequacy of the electronic packaging design relative to conductive heat removal and basic circuit performance could be evaluated under vacuum conditions. With the signal conditioner at 150 microns pressure, functional tests of the BCS were performed at the following two conditions: (1) a cold plate coolant temperature of 115° F and the dc power input to the BCS set at  $\pm 32$  volts; and (2) a coolant temperature of -65° F and the input power set at  $\pm 24$  volts dc. All instrument conditioning circuits were checked for accuracy and manual controls on the console were used to operate the valves and contactors on the load simulator. The manual and automatic Brayton engine control and protective logic, including emergency shutdown, were verified.

Minor problems were uncovered which required the addition of some filter capacitors, however, with one exception the delivered system met all specifications. The low level internal signal conditioner power supplies which convert the engine  $\pm 28$  volt dc to regulated  $\pm 10$  and  $\pm 5$  volt power were too noisy and interfered with the proper operation of the low level circuitry. It was necessary to substitute laboratory-type supplies to complete testing. New power supply boards are presently being designed and fabricated. A separate presentation (Ref. 6), covers in detail the requirements, design, and performance of the Brayton Control System and should be consulted for additional information.

#### Electrical Control Package (ECP)

The ECP was tested at NASA Lewis Research Center in conjunction with the alternator research package. All functions described earlier were investigated including certain of their dynamic characteristics. The details of this testing are reported in Ref. 5 and will only be summarized here. The voltage regulator (VR) and speed control were calibrated and initial functional checking was accomplished using a laboratory type, 3 phase ac power supply. Following this test, the package was incorporated into a test setup which included the Brayton alternator driven by an air turbine, a variable vehicle load, an engine cold plate, and all of the required control and instrumentation. Using this test facility, both the steady-state and dynamic characteristics of the VR and the speed controller were studied. Fig. 9 shows the speed control characteristic in terms of alternator frequency versus parasitic load power. Illustrated on the figure are each of the speed control ranges, i.e., channel A begins conducting at 1198 Hz, channel B begins at 1210 Hz and channel C at 1218 Hz. Each channel has a control range of approximately 14 Hz and overlaps one another by a small amount. The "S" shaped characteristic of each curve is due to the SCR firing angle being linearly proportional to frequency error.

Figure 10 shows the VR shunt field current response to variations in alternator line voltage. Clearly illustrated is the effect of current regulation as the line voltage approaches 120 volts. Additional information relative to the testing of the ECP can be obtained by referring to Ref. 5.

#### DC Power Supply

A number of tests, at various locations are being conducted on the DC Power Supply. The contractor as part of the design and fabrication contract was required to place one unit on endurance test. This life test began in September 1968 and as of 5/14/70 has accumulated 9000 hours of operation with only minor problems.

Of the three additional units fabricated, one is designated as a

spare, one is part of a complete electrical subsystem test under vacuum conditions, and the last unit is supplying dc power for the engine presently under test at NASA Lewis Research Center, Space Power Facility (Fig. 2). Prior to being incorporated into a larger system each supply is given a detailed functional inspection and test. The functional test verifies that all circuits described earlier are fully operational.

Recalling the earlier design discussion which described the origin of the 12-phase ripple (relative to the 1200 Hz fundamental), the resultant output will now be examined. The dc output of the supply is shown in Fig. 11. Summation of the rectified, 12 phase, transformer outputs results in a dc voltage having a 14,400 hertz ripple. Such a design permits the exclusion of filter circuits which reduce conversion efficiency. Plotted in Fig. 12 is supply conversion efficiency against dc load. The dc supply, when operating as a functional part of the Brayton engine, is required to deliver relatively constant power for all steady-state operating conditions except during battery charging. At the nominal operation point the conversion efficiency is seen to be about 88 percent. A more comprehensive account of operating parameters at other than nominal conditions is presented in table III. Shown are the effects of the battery charger loads on supply performance. The lowest overall efficiency, 79.5 percent as seen in table III, results when both battery chargers are operating at a full 8 amp charge rate.

#### Inverters

Testing of the inverters has proceeded very much along similar lines as that the DC Power Supply. The contractor is performing a combined Inverter-Pump Motor Assembly life test which began on April 4, 1969 and had accumulated 5000 hours as of April 14, 1970. Two units (normal engine complement due to redundant heat rejection loop pumps) are being tested under vacuum conditions as part of a complete electrical subsystem test. An additional two units are on the engine under test at the space power facility. As of 5/13/70, 2000 hours of actual engine operation using the inverters to drive the heat rejection loop pumps (usually only one operating at a time), have been accumulated. Performance has been totally trouble free and within design specifications. Test results indicate that the inverter power requirements range from 500 to 600 watts total depending upon the dc bus line voltage and the flow rate being delivered by the respective pump under excitation. A corresponding variation in conversion efficiency occurs, which ranges from 0.73 to 0.80 for the pump load power factor of about 0.65. At greater loads and unity power factor, the efficiency approaches a value of 0.90.

Table IV compares more detailed characteristics of three inverter tests, all with the engine pump motor assembly used as the load. Two of the tests were run at the vendor's facility and one at Lewis Research Center. The data associated with the test run at Lewis is more representative of actual engine operating conditions and indicates the input power to be 510 watts with a conversion efficiency of 0.80 at a power factor of 0.67.

#### Complete Electrical Subsystem

Complete subsystem testing, as opposed to individual component acceptance and performance testing is being performed at two in-house locations. One setup is totally oriented toward an evaluation and endurance test of the electrical subsystem (as shown in Figs. 3 and 4). All engine functions which interface with the electrical subsystem are simulated with external facility equipment. Electrical input (BRU-alternator simulator) is provided by a 3 phase, variable frequency facility power supply. Additional facility instrumentation has been included in the test to allow for cross checking the engine instrumentation and to permit the evaluation of each component's behavior when operating as part of the total subsystem. At the time of this writing, testing of this system was in the early stages with no reportable test data available.

A second complete electrical subsystem is being tested as part of the Brayton engine under test in the Space Power Facility vacuum chamber at NASA Lewis Research Center. Due to the complexity of total engine evaluation requirements, specific data dealing with individual electrical component performance is not available in every case. However, sufficient information is recorded to permit an evaluation of overall electrical subsystem behavior under vacuum

conditions.

Several data points at various engine operating conditions in vacuum are presented to illustrate electrical subsystem performance at several output power levels. The pertinent data are listed in table V. The first grouping of data give typical values of gas loop parameters. The second group, alternator data, is information which is either measured or calculated directly from engine instrumentation. The next group, vehicle load bank, represents the electric power demand of a user. It should be noted that the electrical load profile for a typical mission is seldom constant. The result in Brayton engine performance is the controlled dissipation of more or less power through the parasitic load resistor by the speed control to maintain engine speed within design limits. In order to illustrate this characteristic, data representative of a range of user loads are listed. Within the limitation of instrument accuracies, the resultant value of Parasitic Load Power listed, varies in such a manner as to make the sum of vehicle load power plus total housekeeping power, plus Parasitic Load Power equal gross alternator output power. In the next group engine loads being supplied by the  $\pm 28$  volt dc bus are identified. The value listed for the engine control system is high, and is expected to be reduced by approximately 120 watts when the present series regulated signal conditioner power supplies are replaced by more efficient switching regulated supplies presently being fabricated. Except for periodic battery charging, the dc bus load remains relatively constant regardless of alternator or user power level. The slight imbalance between positive and negative bus totals is due to the large number of signal conditioner circuits which operate positive with respect to ground. The last group, Housekeeping Power, represents all electrical power used by the engine, to operate the engine. The values listed represent power supplied by the alternator to each of the components for their operation. This includes all losses and conversion efficiency penalties.

From table V it can be concluded that a value of approximately 1150 watts is required for housekeeping and that the remainder minus some minimum PLR residual for contingencies is available to the user.

#### Concluding Remarks

Each of the components which comprise the Brayton engine electrical subsystem have been tested as individual packages, as smaller subsystems and as part of the complete engine system. In some cases individual components were tested both at atmospheric pressure and under vacuum conditions over a range of temperatures. In addition the integrated electrical subsystem has undergone testing as a complete package in a configuration where all external interfaces were simulated and as part of a complete Brayton engine. In both of these tests the subsystem was operated in a vacuum environment over a range of cold plate coolant temperatures.

Table II is a compilation of accumulated test hours of individual components and of total subsystem operation. In all but one case, component performance was satisfactory and no redesign was required. The one exception was noisy, low level power supplies internal to the signal conditioner. During the period required for redesign and fabrication of new circuit boards, external supplies were used.

From the results of testing the complete Brayton engine at the NASA Lewis Research Center Space Power Facility, it has been demonstrated that the electrical subsystem fulfills all of its required functions related to control, distribution, regulation, and monitoring of the power conversion system. Startup and shutdown of the engine by the electrical subsystem has also been demonstrated. The total alternator power required to accomplish these functions is a relatively constant housekeeping load of approximately 1150 watts, plus a small parasitic load residual to accommodate slight variations in the system operating point.

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TABLE I. - SUMMARY OF BRAYTON ELECTRICAL SUBSYSTEM HARDWARE CONTRACTS

Hardware Contract	Contractor
NAS3-10935 Brayton Cycle Cooling Pumps	Pesco Products, Cleveland, Ohio
NAS3-10935 Brayton Cycle Inverters	Gulton Industries Inc. E. M. Div., Hawthorne, Calif. (Sub Contract to Pesco Products)
NAS3-10943 Brayton Cycle Control System	AiResearch Mfg. Co. Phoenix, Arizona
NAS3-10936 Brayton Cycle DC Power Supply	Gulton Industries Inc. E. M. Division Hawthorne, Calif.
NAS3-10977 Brayton Cycle Parasitic Load Resistor	Heat Engineering and Supply Co. SanGabriel, Calif.
NAS3-9427 Brayton Cycle Speed Control and Voltage Regulator	AiResearch Mfg. Co. Phoenix, Arizona
NAS3-11784 Brayton Cycle Electrical Control Package	Hayes International, Huntsville, Alabama
NAS3-11898 Brayton Cycle Coldplates	AVCO, Aerostructures Div. Nashville, Tenn.
NAS3-11257 Brayton Cycle Circuit Breakers	Hartman Electric, Mfg. Co. Mansfield, Ohio

TABLE II. - BRAYTON ENGINE ELECTRICAL COMPONENT AND  
SUBSYSTEM TEST RECORD AS OF 5/13/70

Description	Number of units tested	Total hours all units	Max. hours single unit
Alternator (BRU)	4	3, 245	2340
Engine Control System	2	2, 140	2130
Electrical Control Package	2	2, 060	2050
DC Power Supply Package	4	11, 700	9000
Inverters	7	9, 122	5550
Electrical Subsystem Test	1	(In final checkout)	
Complete Engine	1	2, 000	2000

TABLE III. - BRAYTON POWER SUPPLY EFFICIENCY FOR ALL  
COMBINATIONS OF CHARGING RATES

Power, watts	Charging rate				
	0	1/4	1/2	3/4	Full
3 $\phi$ ac input	1402.0	1661.5	1869.0	2110.2	2374.4
DC bus output	1244.0	1244.0	1244.0	1244.0	1244.0
Charge output	0	160.0	320	480	640
Total output	1244.0	1404.0	1564.0	1724.0	1884.0
Percent efficiency output/input	88.9	84.5	83.6	81.7	79.5

TABLE IV. - COMPARISON OF INVERTER OPERATING CHARACTERISTICS AT  
VARIOUS VOLTAGE AND PUMP OPERATING CONDITIONS

Unit Tested	Input			Flow rate	Output					
	Volts dc	Amps dc	Watts		Volts/PH	Amps/PH	VA Total	Watts Total	Power factor	Efficiency, percent
Unit for SPF (At Vendor)	58.3	10.4	605	0.45	46.2	8.90	713	457	0.64	76
Life test (At Vendor)	59.2	10.2	602	0.45	46.8	8.85	715	446	0.63	73
Unit for CW-19 (At LeRC)	55.0	9.25	510	0.39	44.1	8.00	610	406	0.67	80

TABLE V. - TYPICAL ELECTRICAL SUBSYSTEM PERFORMANCE FOR  
A RANGE OF ENGINE AND USER POWER LEVELS  
[ Testing at SPF under vacuum conditions. ]

Description	Data Run Number			
	2, 862	3, 742	4, 053	4, 102
<u>Engine Parameters</u>				
Turbine inlet temperature, °F	1, 607	1, 609	1, 603	1, 606
Compressor inlet temperature, °F	81	81	83	83
Compressor outlet pressure, psia	44.2	35.1	35.1	35.0
Average electronic cold plate temperature, °F	94	98	96	98
<u>Alternator Data</u>				
Average line to neutral phase voltage, rms	118.2	118.0	119.1	118.8
Average line current per phase, rms	34.8	27.4	25.6	26.4
Total volt-amperes, rms	12, 320	9, 700	9, 150	9, 400
Power output, watts	11, 980	9, 340	9, 050	9, 140
Frequency, hertz	1, 208	1, 231	1, 200	1, 210
Power factor, percent	97.0	96.4	99.0	97.0
<u>Vehicle Load Bank (User Load)</u>				
Average line to neutral phase volts, rms	118.2	0	119.0	118.9
Average line current per phase, rms	27.0	0	21.8	19.4
Total volt-amperes, rms	9, 600	0	7, 800	6, 910
Power output, watts	9, 287	0	7, 868	6, 936
Power factor, percent	96.5	-----	100	100
<u>Parasitic Load Power</u>				
Total PLR power, watts	1, 562	8, 190	58	1, 081
<u>Engine ±28 Volt dc Bus Load</u>				
<sup>b</sup> Inverter input (total), watts	510	510	510	510
<sup>c</sup> Engine control system (total), watts	352	215	234	211
Battery chargers, watts	0	0	0	0
Total +28 volt bus, watts	574	561	584	559
-28 volt bus, watts	288	295	262	266
<u>Housekeeping Power</u>				
DC Power Supply (assuming 86% efficiency), watts	1, 000	995	984	960
<sup>b</sup> ECP speed control, watts	80	154	63	76
<sup>b</sup> ECP voltage regulator, watts	51	51	51	51
Total predicted, watts	1, 131	1, 200	1, 098	1, 087
Calculated Housekeeping power, ALT. - (V. L. + P. L. R.), watts	1, 131	1, 150	1, 124	1, 123

<sup>a</sup>Instrument error required back calculation of this data point.

<sup>b</sup>Predicted values based on separate component testing.

<sup>c</sup>Value listed is expected to be reduced by about 120 watts with the replacement of low level power supplies in the signal conditioner.



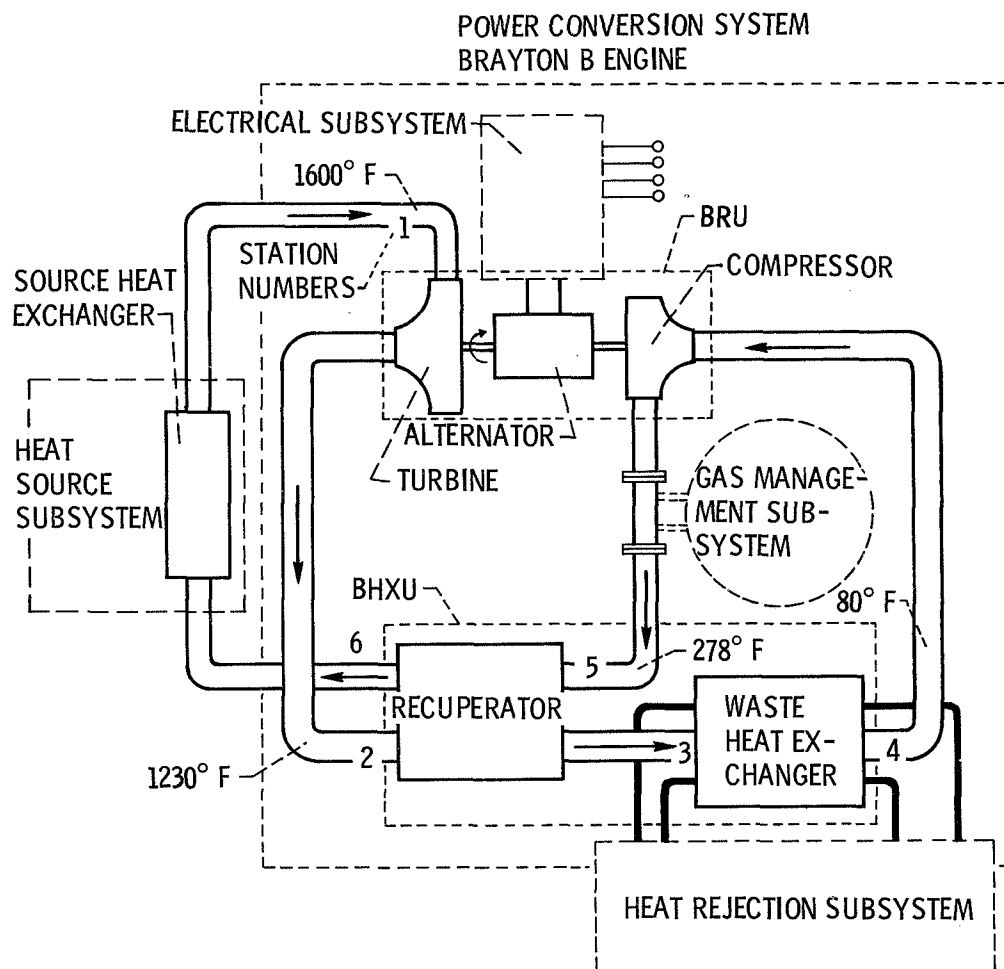
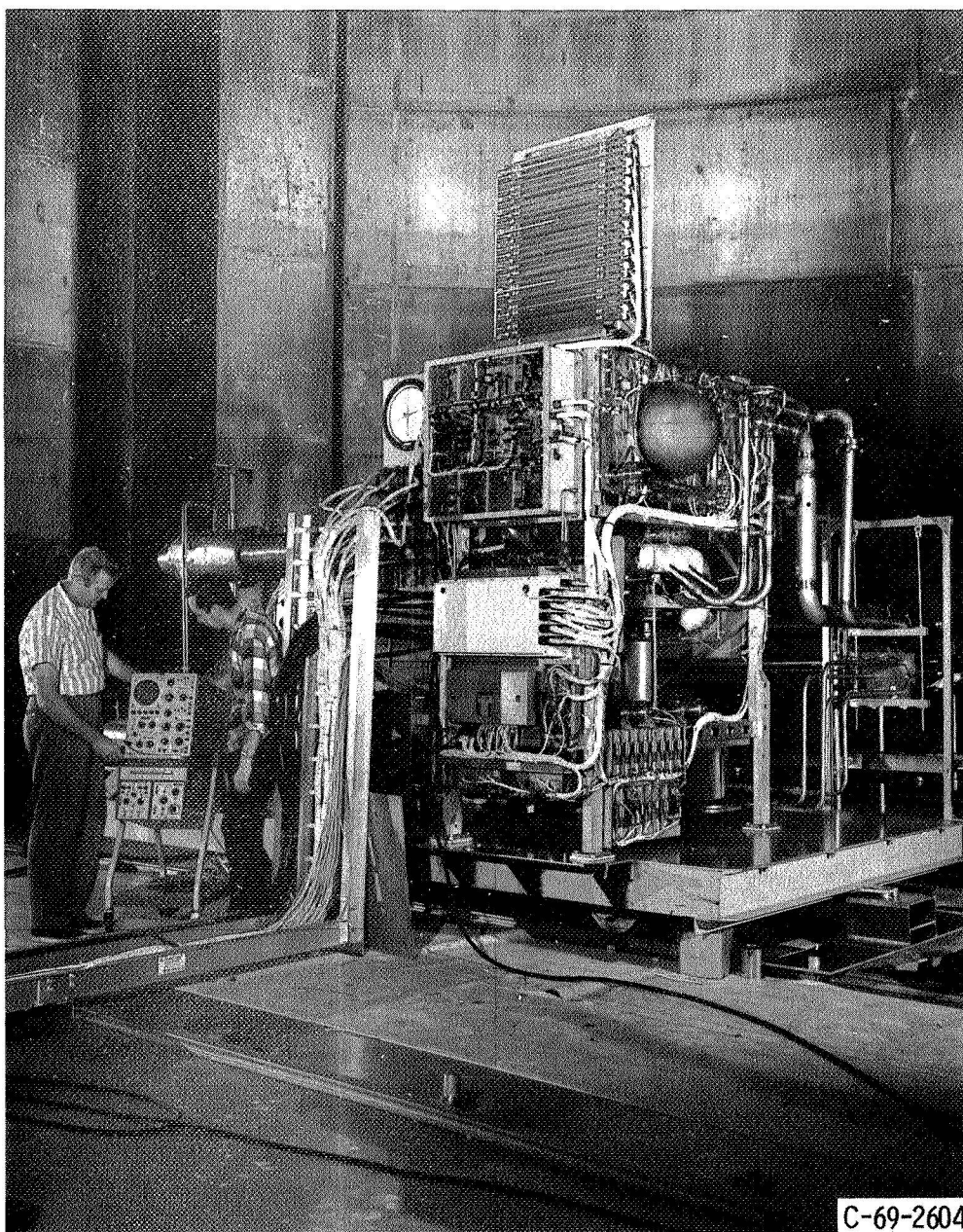


Figure 1. - Schematic diagram, Brayton power system.



C-69-2604

Figure 2. - The Brayton Power System test engine at the NASA Space Power Facility.

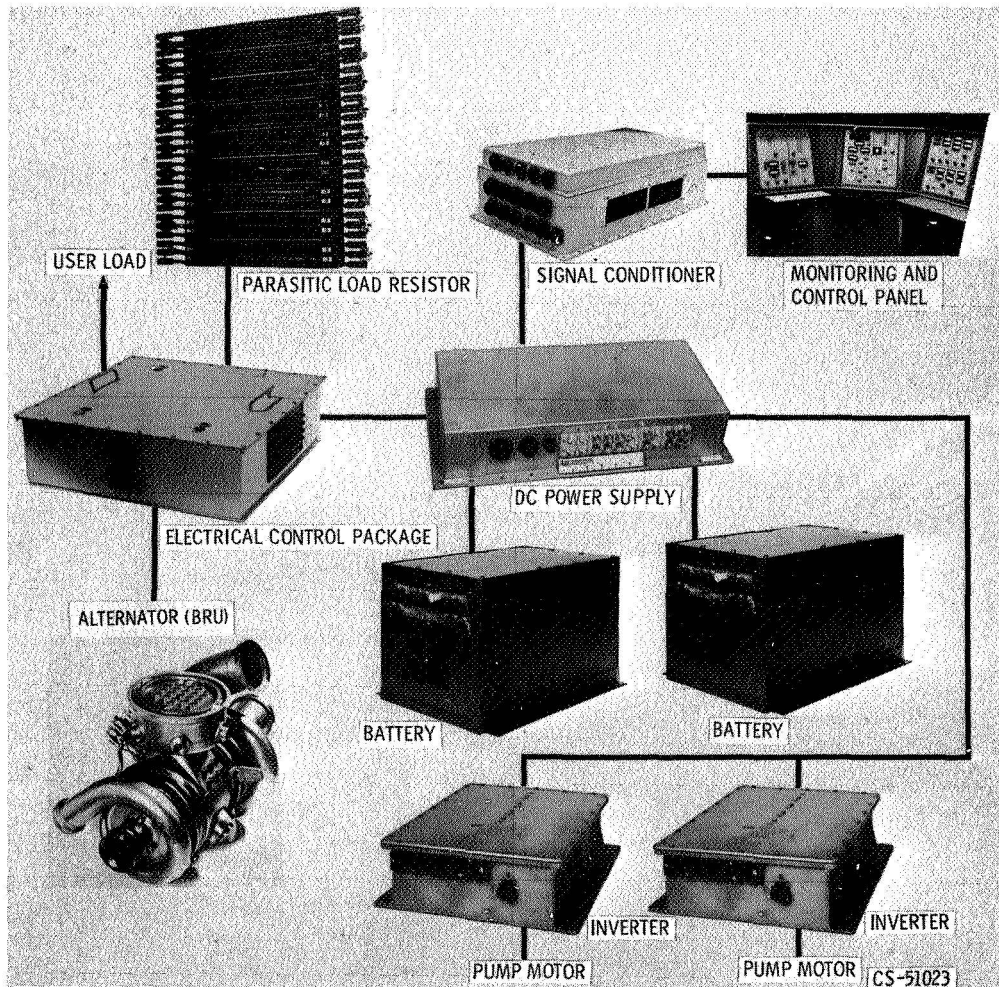


Figure 3. - Brayton electrical subsystem components.

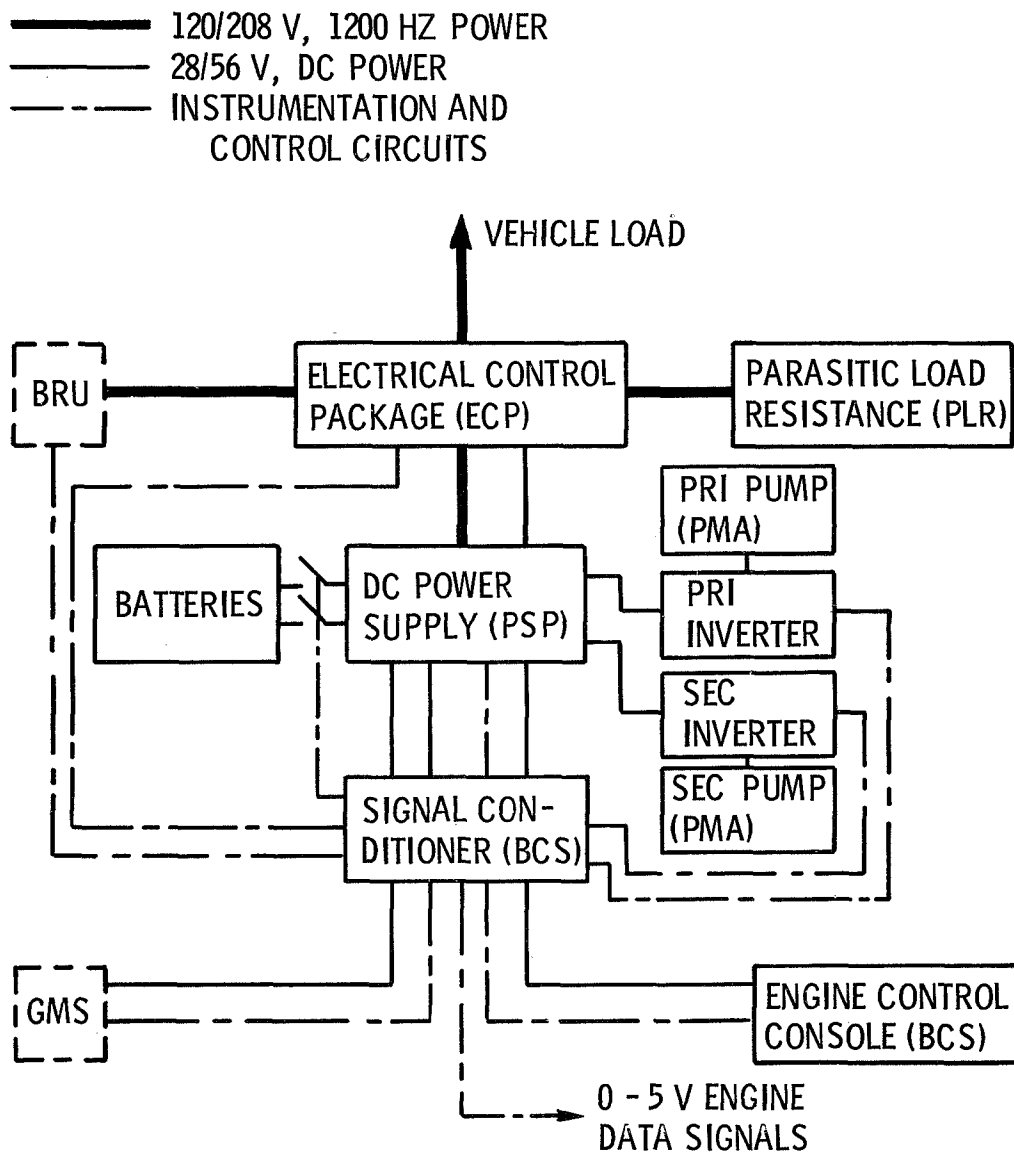


Figure 4. - Block diagram of the Brayton electrical subsystem.

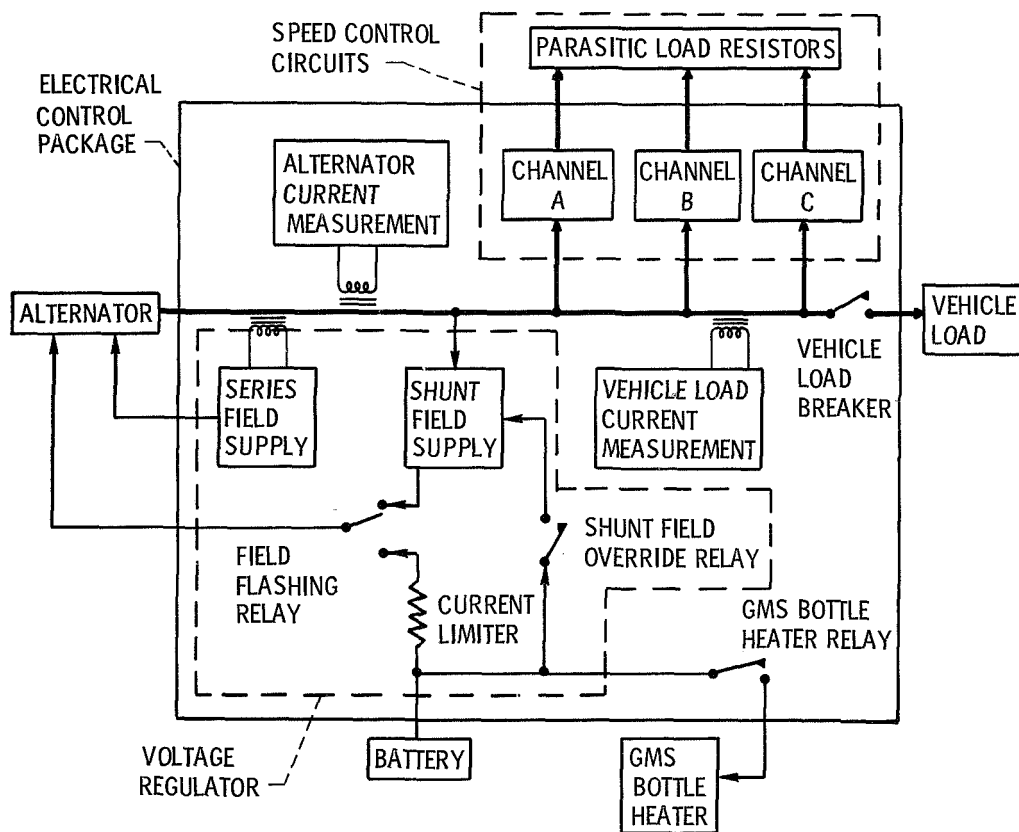


Figure 5. - Block diagram of the Electrical Control Package.

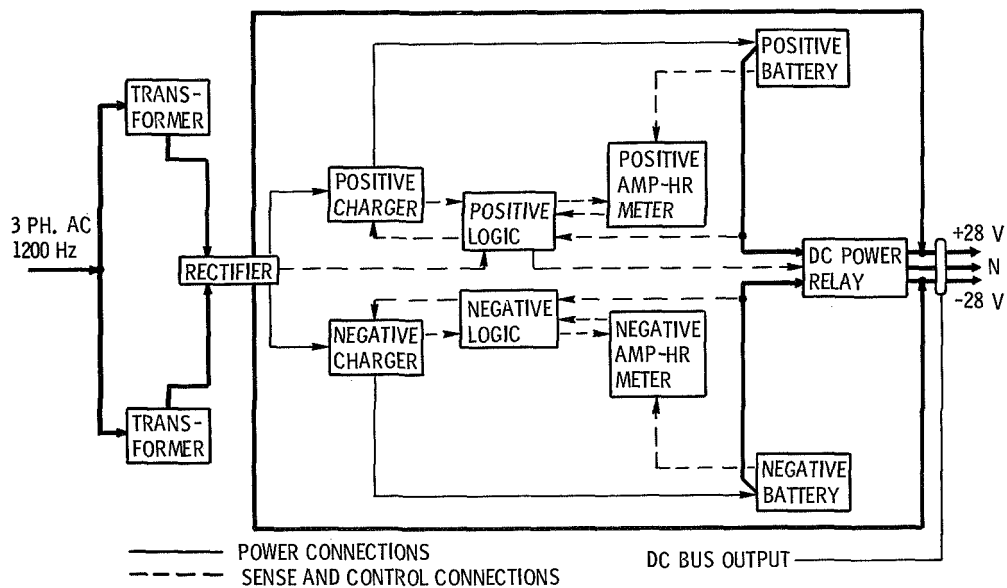


Figure 6. - Block diagram of the DC Power Supply.

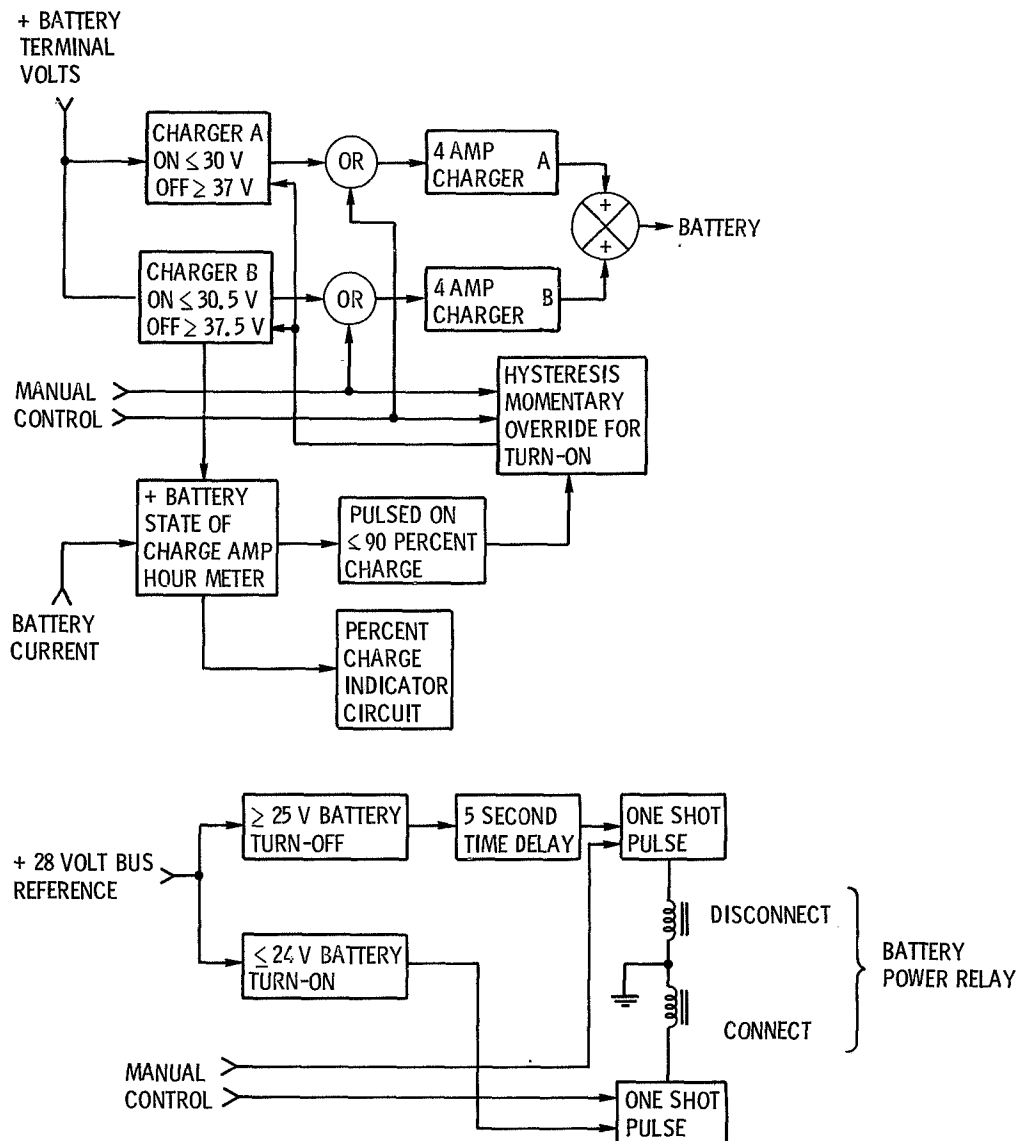


Figure 7. - Logic diagram for +28 half of the Brayton DC Power Supply.

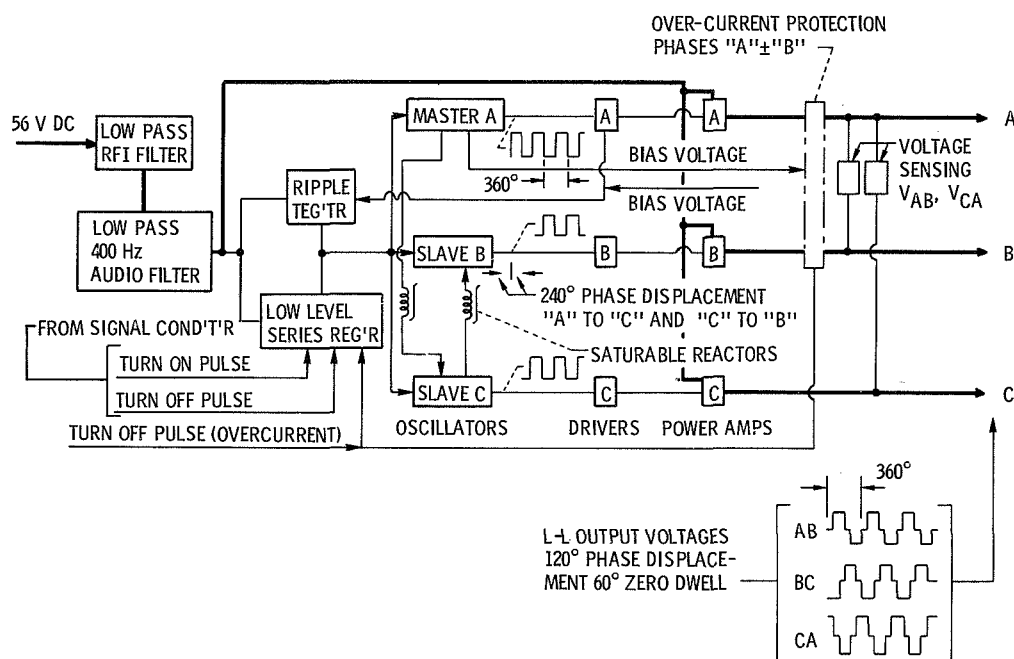


Figure 8. - Inverter-block diagram.

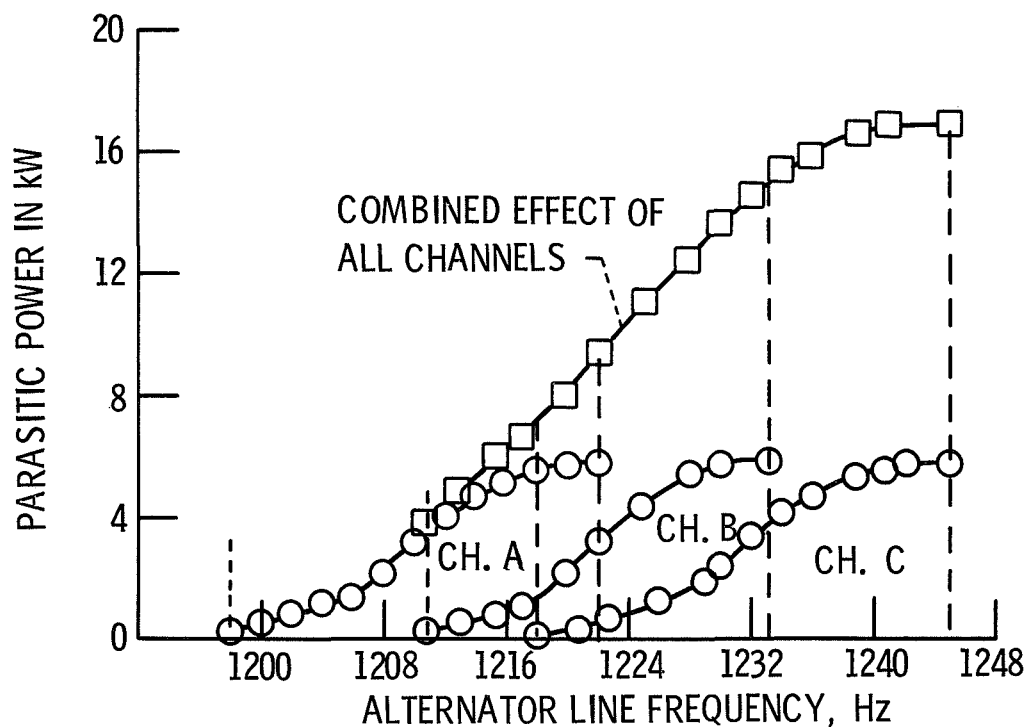


Figure 9. - Calibration curves for the Brayton system speed controller.

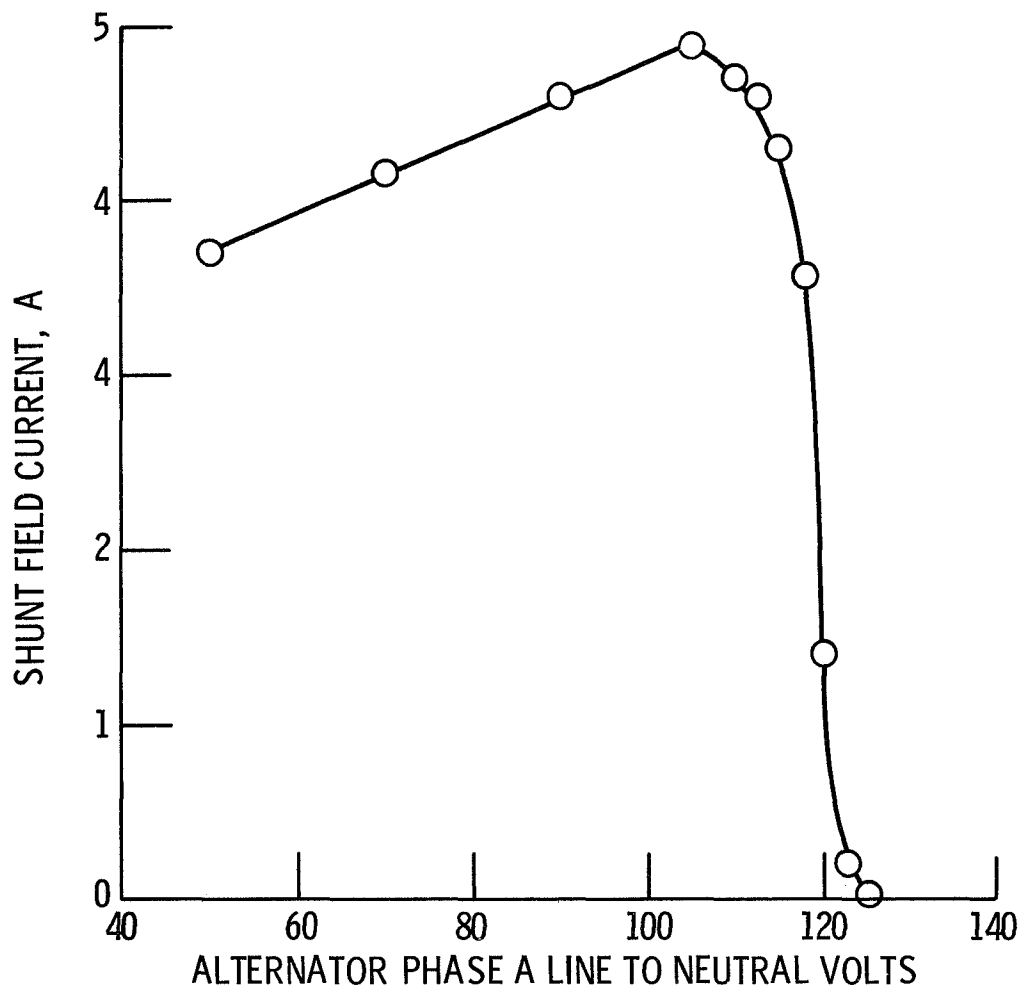
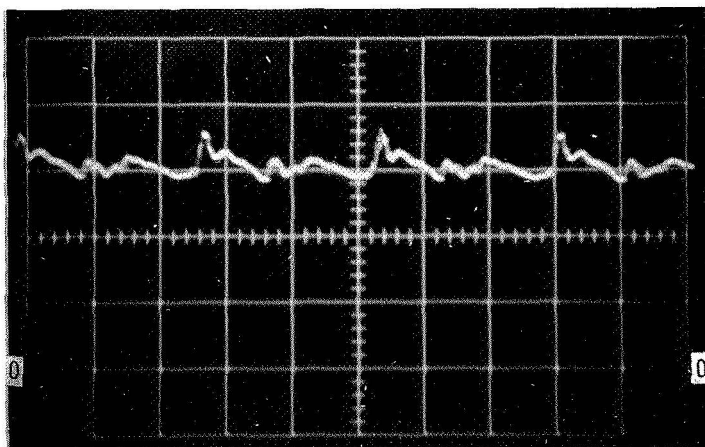


Figure 10. - Voltage regulator characteristics shunt field  
amps versus phase A volts.





TIME SCALE = 50  $\mu$ s/div.  
MAG. SCALE = 10 VOLTS/div.  
RIPPLE VOLTAGE + 28 VOLT  
BUSS TO COMMON

Figure 11. - Photograph of the +28 volt dc output of the  
Brayton DC Power Supply.

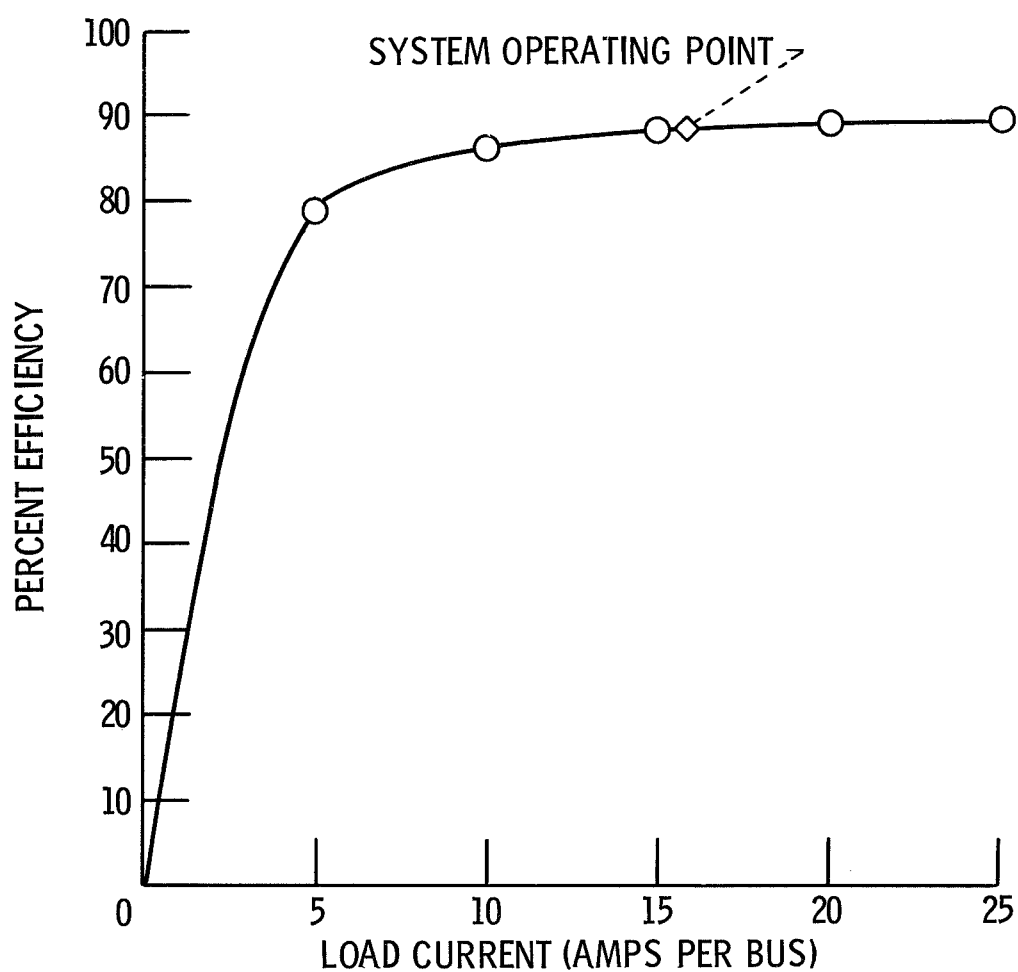


Figure 12. - Brayton DC Power Supply efficiency versus load characteristics.